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Finite element analysis for torsion behavior of flat web profile beam steel section with opening

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Abstract

The construction of modern commercial buildings should always incorporate building services while reducing the cost of steel. A frequently used solution is to provide openings at the web of the beams and girders to enable services to pass through. The main objective of this paper is to determine the angle of torsion of a flat-web (FW) profile steel section with openings of different shapes and sizes using LUSAS software. A model consisting of a FW profile beam steel section of five shapes and three sizes of openings has been developed. The shapes of opening are circle, square, regular octagon, C-hexagon, and regular hexagon. The sizes of the opening are 0.5 D, 0.6 D and 0.8 D; D is the height of the web. Based on the results of the analytical investigations, the best shape of the opening is C-hexagon, and best size is 0. 5 D in resistance torsion compared with a FW profile section without opening. When the length of the beam section becomes longer, the value of the rotation angle increases. In general, the value of the angle of rotation for all shapes and sizes is close to the value of the angle of rotation for a FW profile without opening. Hence a flat-web section with opening is suitable in many cases to reduce cost and weight of steel.

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Keywords: Flat web profile; finite element analysis; torsion resistance; rotation angle; web opening.

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1. Introduction

Previous studies of the torsional behavior of the normal flat web (FW) beam and trapezoidal web beam in various sizes using finite element analysis [1,2] indicated that the torsional rotation of the trapezoidal web steel section is less than that of the flat web steel section. A flat web beam has a lower resistance to lateral torsional buckling compared with a trapezoidal corrugated web [3]. The web opening of a steel I-beam decreases the critical bending moment associated with buckling instability. The decrease basically depends on the ratio between opening height (HO) and beam height (H) [2]. Web opening may change the mode of the beam buckling instability from lateral torsional buckling to local buckling [4].

Despite the advantages of flexibility in construction or better outlook, placing an opening may reduce the strength of the section if it was not properly designed. In addition, many researchers investigated the behavior of the opening on shear and buckling, but no study has been conducted on the beams with openings under torsion. In the present paper, the torsional behavior of a flat web (FW) steel section with openings will be examined by numerical study (LUSAS software) [5] to determine the displacement, δ, and torsional rotation, θ. The numerical model is extended to determine the variables such as size of the opening and shape of opening that cause variation in torsional rotation.

Nomenclature

FW	Flat Web	θ	Torsional rotation
D	Depth of beam section	B	Breadth of beam
t_f	Flange thickness	t_w	Web thickness
δ	Displacement	L	Length of specimen

2. Finite Element Analysis of Torsion

A point load was applied at four different points at one end of the beam model. At the other end, the nodes were restrained in the x, y and z directions. Linear analysis was conducted to obtain the torsional rotation, θ, for all models. Some material properties were kept constant throughout the analysis:

Young's Modulus, $E = 2.09 \times 10^5$ N/mm^2
Poisson's ratio, $\nu = 0.3$
Shear Modulus, $G = 79 \times 10^3$ N/mm^2

To study torsional behavior, some variables were considered, such as the load values from 1 kN to 5 kN, the shape of web opening such as circle, square, regular octagon, regular hexagon, and C-hexagon as shown in Fig. 1, and three sizes of opening, as shown in Table 1. The beam size used in this study is a 200×120×9×5 mm flat-web beam profile steel section. The first part of the analysis is determining the best shape and size of opening for a specimen with a length of 1 m. The best size with different shapes of opening and load value of 1 kN will be applied to different beam lengths to analyze the effect of length on the twisting angle. The lengths of specimen in this study are 1 m, 2 m, 3 m, and 6 m.

Table 1. Sizes of web opening

Beam size (mm) ($D \times B \times t_f \times t_w$)	Opening size (mm)	
200×100×9×5	0.5D	100
	0.6D	120
	0.8D	160

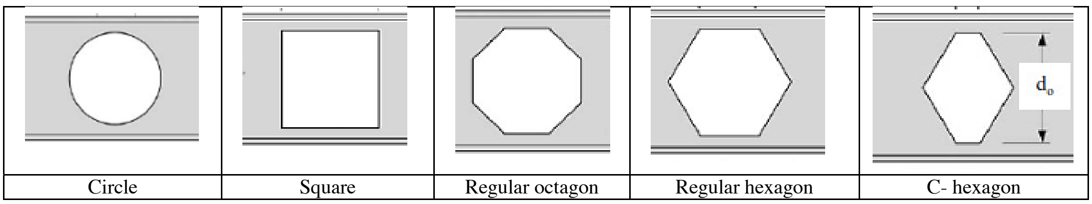

Fig. 1. Geometric configuration of web openings [7]

3. Result of Analysis

Five shapes of openings have been used in this study to observe the differences in displacement and torsional rotation under torsion load. Results show that the shape of opening affects the displacement and torsional rotation values. Torsional rotation, θ, is calculated using Eq. (1). Table 2 shows the displacement and torsional rotation of all FWs with different web opening shapes and sizes and FWs without opening at 1 kN. Based on the numerical analysis, C-hexagon was determined to be the best shape of opening because the angle of rotation is very small and significantly close to the FW beam without opening. The differences between these values do not exceed one percent. In addition, the C-hexagon-shaped opening is very suitable in construction to reduce the weight and minimize the cost of steel. The regular hexagon is the second shape after C-hexagon that implies that the torsional rotation, θ, for this shape of opening is still close to the FW without an opening. The next best shapes are regular octagon, square, and circle.

$$\theta = tan^{-1}\frac{\delta}{(\frac{D}{2})} \qquad (1)$$

Table 2. Displacement, δ and torsional rotation, θ values for FW with and without web opening

Web opening shape	0.5D		0.6D		0.8D	
	Displacement, δ (mm)	Torsional rotation, θ (o)	Displacement, δ (mm)	Torsional rotation, θ (o)	Displacement, δ (mm)	Torsional rotation, θ (o)
Circle	1.746	1.000	1.763	1.010	1.780	1.020
Square	1.728	0.990	1.746	1.000	1.758	1.007
Regular octagon	1.726	0.989	1.735	0.994	1.752	1.004
Regular hexagon	1.725	0.988	1.733	0.993	1.751	1.003
C-hexagon	1.721	0.986	1.730	0.990	1.746	1.000
FW without opening	1.710	0.980	1.710	0.980	1.710	0.980

The closeness of torsional rotation values between C-hexagon, regular hexagon, and regular octagon shapes can be observed because of the similarity of the form. However, even if the differences in shape give different values of torsional rotation, these values are still close to each other. Similar findings was reported in the optimum design of steel structures with web openings [6]. Beams with web openings of various shapes but with the same opening depths and lengths have a similar structural performance. However, beams with openings of the same length but different depths yield different results.

Analysis also shows that the size of the opening has a slight effect on torsional rotation values. Furthermore, the best size of the opening in this study is 0.5 D because the value of displacement and torsional rotation of this size is very close to the FW beam without an opening compared with other sizes. Similar finding was reported in strengthening the steel beam around the rectangular web openings [7]. A size of opening of 0.5 D has small stress intensity compared with other opening depths such as 0.65 D and 0.75 D.

In this study, openings of different sizes have close torsional rotation values, θ and similar finding was reported in the Vierendeel mechanism in steel beams with circular web openings [7]. The two sizes, 0.5 D and 0.75 D, were very close to each other in shape, despite the significant difference in the opening sizes. In conclusion, the differences of the angle of rotation values of different shapes and sizes are close to each other with a length of 1 m.

3.1. Comparison between percentage angle of rotation for FW with opening and without opening

As previously described, five load values, three sizes, and five shapes of openings were used to observe the effect of the opening on torsion. The results of the lowest and highest loads are summarized in Table 3 for FW with 0.5 D, 0.6 D, and 0.8D openings.

Fig. 2 shows the relative angle of rotation of FW with different opening shapes and a size 0.5 D compared with the FW without opening. With a load of 1 kN, the relative angles of rotation are 2.00%, 1.23%, 0.97%, 0.84%, and

0.70% for the FW with circle, square, regular octagon, regular hexagon and C-hexagon shaped openings, respectively. With a load of 5 kN, the relative angles of rotation are 2.12%, 1.38%, 1.13%, 0.99%, and 0.86% for the FW with circle, square, regular octagon, regular hexagon and C-hexagon shaped openings, respectively. The value of the relative angle shows the percentage difference between FW with opening and FW without opening. Based on these results, the percentage angle of rotation increases with the load value for all shapes. The increase in the angle of rotation for FW with opening does not exceed 2.12%, and the C-hexagon shape has the lowest angle of rotation relative to other shapes with an opening size of 0.5 D.

Table 3. Summary of the percentage difference angle of rotation, θ compared to that of FW without opening of 0.5D, 0.6D and 0.8D at 1 kN and 5 kN.

	Percentage difference angle of rotation, θ compared to that of flat web (FW) without opening (%)					
Opening Shapes	0.5D		0.6D		0.8D	
Load (kN)	1 kN	5 kN	1 kN	5 kN	1 kN	5 kN
Circle	2.00	2.12	2.65	2.78	3.40	3.50
Square	1.23	1.38	2.14	2.28	2.8	2.93
Regular octagon	0.97	1.13	1.52	1.66	2.53	2.61
Regular hexagon	0.84	0.90	1.33	1.47	2.34	2.46
C-hexagon	0.70	0.86	1.10	1.25	2.00	2.16

The relative angle of rotation of FW with different opening shapes of size 0.6 D and 0.8 D compared with that of the FW without opening are shown in Fig. 3 and Fig. 4, respectively. In this case, the angle of rotation percentage increases with the load value. The increase in the angle of the rotation value of a beam with an opening size 0.6 D is higher than the increase in the angle of the rotation value of a beam with an opening size 0.5 D.

3.2. Effect of beam length on the angle of rotation for flat web with and without opening

The effect of length on the angle of rotation has been investigated using the best size of opening found earlier (0.5D) with five opening shapes and load value of 1 kN. Four different lengths, namely, 1, 2, 3, and 6 m, have been used in this study to determine the effect of length on the angle of rotation. Fig. 5 shows the torsional rotation of FW beam profile section with and without opening with different beam lengths. Results show that if the beam section is longer, the angle of rotation increases for both specimens. Hence a difference exists between the angles of rotation. However, this difference is still the smallest among all opening shapes and sizes. The slight difference is likely because of the adoption of the torsion on the flanges more than the web, which implies that the flanges can resist torsion more than the web of the beam.

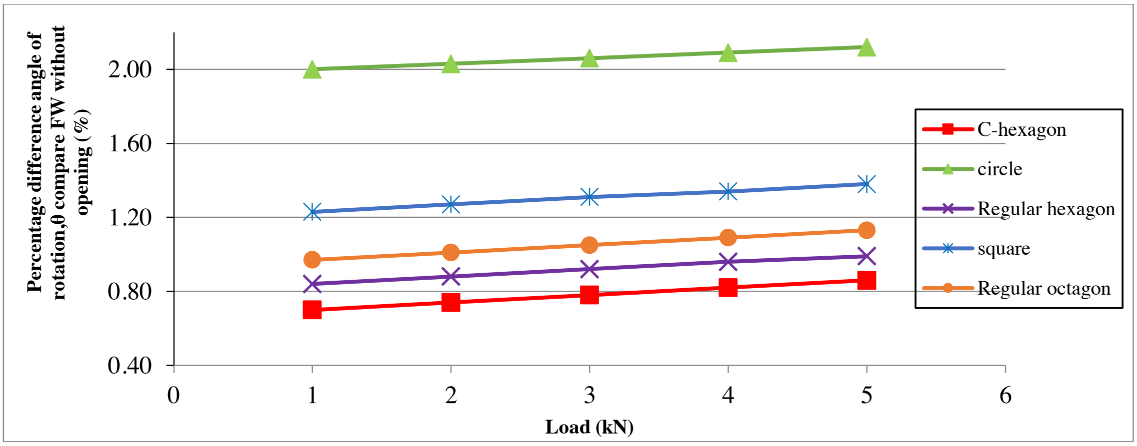

Fig. 2. Percentage difference angle of rotation, θ of FW with opening of size 0.5D as compare to that of flat web (FW) without opening

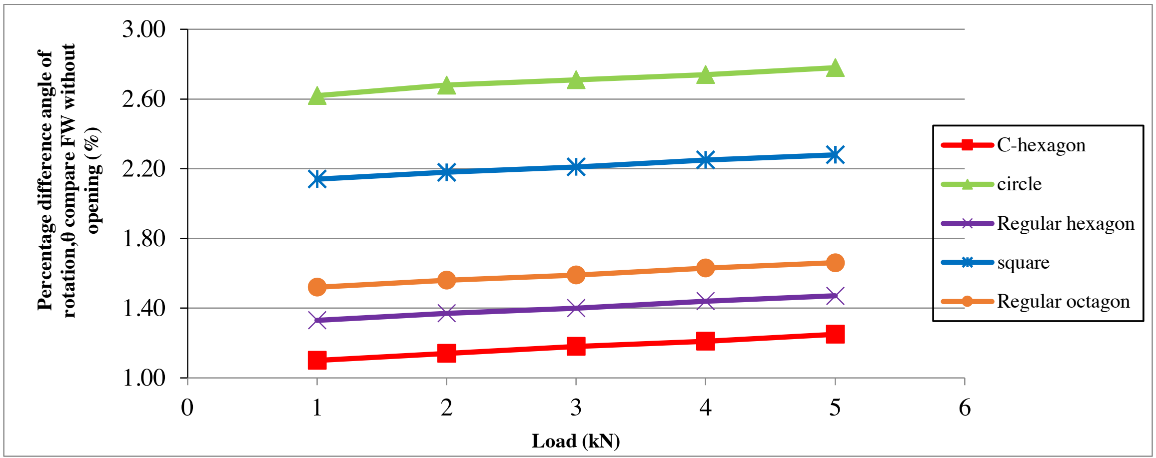

Fig. 3. Percentage difference angle of rotation, θ of FW with opening of size 0.6D as compare to that of flat web (FW) without opening.

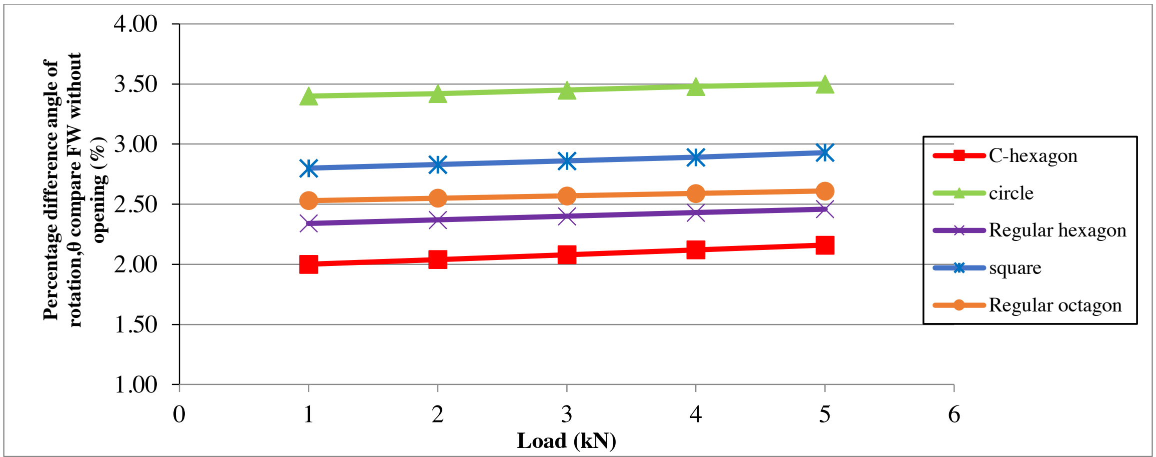

Fig. 4. Percentage difference angle of rotation, θ of FW with opening of size 0.8D as compare to that of flat web (FW) without opening

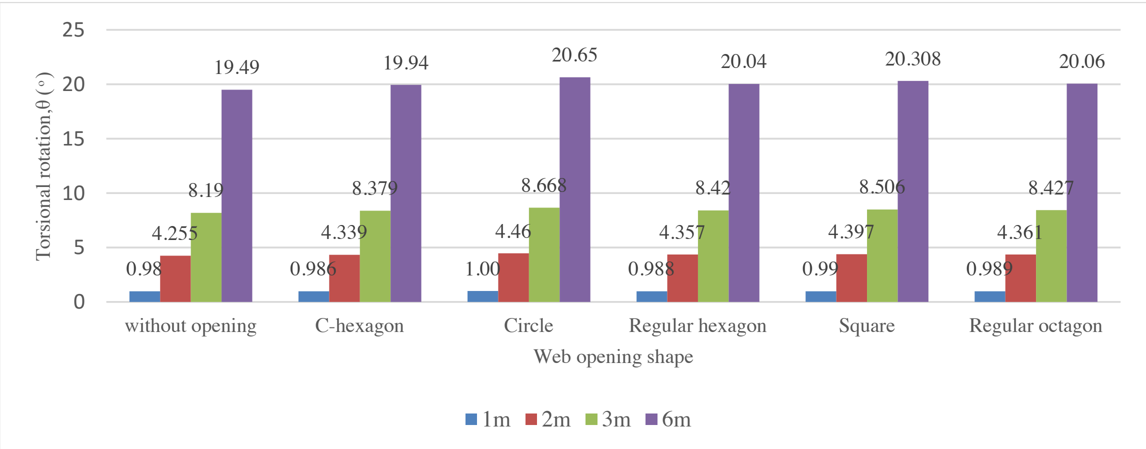

Fig. 5. Torsional rotation, θ of FW with and without opening with length of 1m. 2m, 3m and 6m under 1 kN load

Conclusion

The following conclusions can be drawn from the present study:

- Many variables can be stimulated from the theory of torsion. Different values of variables yield varying results. The variables in this study are the shape of opening, size of opening, length of the beam, and load values.
- The analyses of the flat web section with and without opening indicates that the value of the angle of rotation for FW without opening is smaller than the angle of rotation of FW section with opening. However, the difference is small, which implies that the torsion values for both FW section with opening and without opening are close to each other. Hence, the FW with opening is suitable in many cases of construction to reduce cost.
- Five opening shapes were used in this study to observe the effect of the shape opening on the torsion value. The best shape of opening is the C-hexagon. The regular hexagon shape, regular octagon, square and circle are the second, third, fourth, and fifth best shapes, respectively.
- Three sizes of openings were used in this study to observe the effect of opening size on the torsion value. The best size of opening is 0.5 D that makes the torsion value of the FW section with opening close to the torsion value of the FW section without opening. The second size of opening is 0.6 D, followed by 0.8D; D is the depth of the web.
- Four lengths used in this study, namely, 1, 2, 3, and 6 m. These lengths were used a load value of 1 kN. In this study, the angle of rotation increases with beam length.

Based on the results, it can be concluded that a FW steel section without opening and a FW steel section with opening have similar or close resistance to torsion loading.

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